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An active method to reduce magnetic noise for measurements of human magnetic fields

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Abstract

Levels of artificial and geomagnetic fields are one million times higher than the levels of human magnetic fields. Therefore, the measurement of weak magnetic fields often requires shields which reduce external magnetic noise. Today, as opposed to expensive magnetically shielded rooms (MSRs), active shielding is a less expensive method of suppressing magnetic noise. Active suppression of magnetic noise is realized by a method of negative feedback. Based on this principle, we develop a device for the reduction of magnetic noise in three orthogonal planes. In this paper, we present the design and realization as well as first test measurements with this active magnetic shielding. We have obtained a reduction of 25 dB for external noise interferences. In the future, this device will allow to carry out magnetic measurements of biological objects without expensive antimagnetic rooms.

1 Introduction

For the measurement of human magnetic fields very sensitive magnetic sensors are used. Each magnetometer has its own level of white noise. Low intrinsic white noise does not mean yet that measurements of magnetic fields of biological objects can not be carried out with high accuracy. High accuracy is impeded by high levels of natural variations of the geomagnetic field of the earth or, additionally, by the large noise levels of an artificial origin, respectively. For example, the noise level of the electricity under common laboratory conditions or in a city hospital can exceed biomagnetic fields a million times. Noise from electrotransport has pulse character and exceeds tens of nT even in distances of more than hundreds of meters. The spectrum of magnetic noise in cities practically completely overlaps the spectra of signals from biological objects. Usually, the geomagnetic field dominates over a magnetic field of an artificial origin. The natural level of geomagnetic field variations range between 30 and 60 µT, and can sharply change during a day within the limits from 50 to 100 nT. Natural geomagnetic field variations are a serious problem for biomagnetic research. That is to say, natural and artificial magnetic influences prohibit measurements of biomagnetic fields.

Different methods are known for the suppression of magnetic noise: differential measuring circuits [1], passive shielding by ferromagnetic materials [2] and active compensation by a feedback coil system [3]. The usage of differential measuring circuits is reasonable only in the case that the source of noise is located in a distance which exceeds distance between the differential sensors at least twice.

Most biomagnetic measurements are performed in a magnetically shielded room (MSR). A MSR consists of several layers of highly permeable material for the magnetic shielding and aluminium for the eddy current shielding. Nevertheless, MSRs are costly, difficult to install, too cramped to be comfortable for patients, and inconvenient for intensive care patients, who are usually dependent on bedside medical devices. It is for these reasons that alternative solutions are needed.

In this work we present a method for suppressing magnetic fields, established by means of a closed negative feedback loop. It consists of magnetic field sensors included in the differential circuits and an enhanced Helmholtz coils set. Such a method allows increasing efficient suppression of external magnetic noise.

2 Methods

The level of magnetic noise in the working volume of a biomagnetic sensor can be lowered by a method are known as negative feedback loop. For this purpose, we separate noise from the signal, invert it and return it back to the Helmholtz coils as shown in Figure 1.

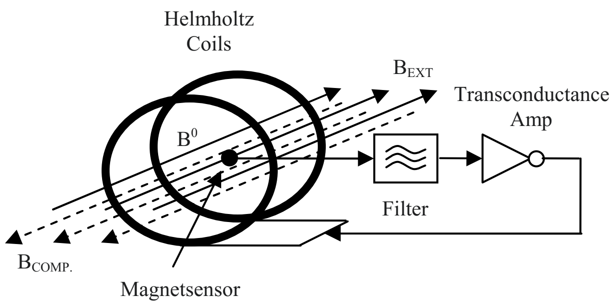

Figure 1: The basic diagram of the negative feedback loop. B_{COMP} is the compensation magnetic field formed by the Helmholtz coils. B_{EXT} denotes the external magnetic noise.

Subsequently, the Helmholtz coils create a magnetic field in the opposite direction and intensity to the external noise, thus compensating the external magnetic noise.

To increase the efficiency of the magnetic noise suppression, we have added a second-order gradiometer to our system [1]. The block diagram of the second-order gradiometer with active magnetic shielding is presented in Figure 2. In the diagram, the magnetic sensors (S_1, S_2) and (S_2, S_3), respectively, form two pairs of first order gradient instruments. The subtraction of a signal from one gradiometer from another is essentially a second-order gradiometer.

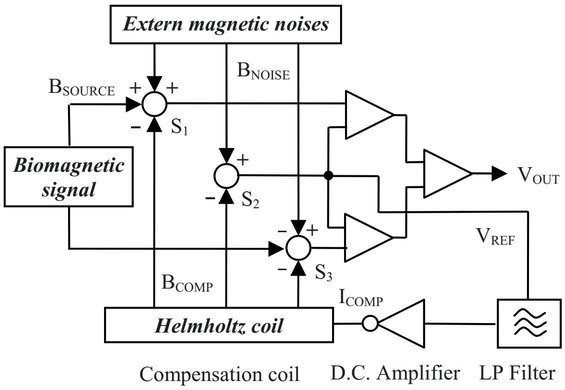

Figure 2: Schematic of the second-order gradiometer with active compensation of external magnetic noises.

The reduction of the magnetic noise fields in the volume of the sensor S_1, S_2, and S_3 is accomplished by supplying a current to the negative feedback input I_{COMP} on the Helmholtz coils.

For an effective reduction of magnetic noise in the measured volume, we are applying a Helmholtz coil system forming an enhanced architecture [4], which consists of three pairs of rings located in three mutually orthogonal directions. For the ideal compensation of magnetic fields our system (see Figure 4) is designed in the form of circular Helmholtz coils fixed in a distance equal to the radius of the rings. Between these pairs of coils the homogeneous magnetic field is induced whose direction is parallel to the axis linking the centers of the coils.

The diameter of the rings is defined by the necessary volume for a homogeneous magnetic field according to the size of the measured object, considering that the volume of the homogeneous field of such design is about one thousands of the volume enveloped by the ring system. Therefore, the minimal diameter of ring system can be calculated using the following equation:

$$d = \left(\frac{v \cdot 10^3 \cdot 3}{\pi \cdot 4}\right)^{1/3} \cdot 2 \quad , \qquad (1)$$

where v is the necessary volume of a homogeneous magnetic field.

The number of turns per coil ring defines the magnetic field generated in the centre of the coil arrangement for a given coil current. The magnetic field B in the centre of a round coil pair is given by the following equation:

$$B = \mu_0 \cdot 0.9 \frac{NI}{R} \quad , \qquad (2)$$

where μ_0 is the magnetic constant $\mu_0 = (4\pi \cdot 10^{-7})$, I denotes the coil current in amperes, R is the average radius of coils, and N is the number of windings of both coils.

For simultaneous suppression of an external magnetic noise all three orthogonal planes x, y, z, have to measured by three mutually orthogonal (second order) gradiometers. Each second order gradiometer consists itself of three individual sensors S_1 S_2 and S_3 (see Figure 2).

Next, we shall give some thought to the arrangement principle of the magnetic sensors in one single direction. The sensors S_1 S_2 and S_3 have to be fixed collinearly (see Figure 3). Sensor S_2 measures the (rough) level of the external field and must be placed near the center of the ring system. This sensor provides the magnetic compensation B_{COMP} for low-frequency magnetic noise B_{NOISE}. Thus, this compensation provides a magnetic offset to center the biological objects' magnetic fields on the zero line of the high sensitivity sensors S_1 and S_3. Sensor S_1 and S_3 should be placed close to the center of the ring system around the measured object. To increase the level of the sensor signal, sensors S_1 and S_3 should be fixed as close as possible to the measured object B_{SOURCE}. The signal received from sensors S_1 and S_3 passes through a differential circuit which measures the signal difference between these two sensors. As a result, the output amplitude V_{OUT} will change proportionally to the local magnetic field which acts on sensors S_1 and S_3.

Magnetic field sensors usually have restrictions concerning the sample frequency. If the feedback is not limited up to the maximum sampling frequency of the sensor, the system may enter a self-generation state, i.e., a resonance condition. Therefore, to limit the sampling frequency, a low pass filter must be located between the sensor and the inverting direct current amplifier.

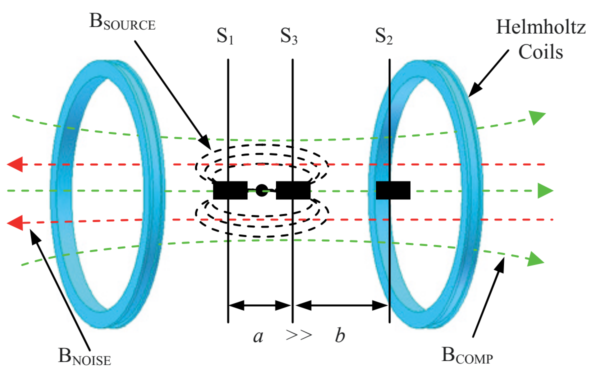

Figure 3: The arrangement of the magnetic sensors

3 Results

So far, we have built an experimental setup which consists of three pairs of Helmholtz coils (see Figure 4). Each pair of coils covers one of the three mutually orthogonal directions.

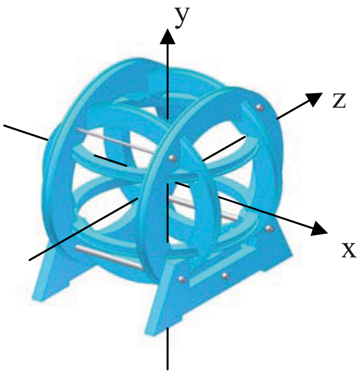

Figure 4: The Helmholtz-Coils in three dimensions systems.

To reduce the cost and weight of the compensations coils construction, we have made the base of rings from Styrofoam. The minimal diameter of the coils (see Table 1) has been calculated considering the expected dimensions of the targeted biological objects and the resulting necessary volume of the homogeneous magnetic field. As the vision of our research is the measurement of the human heart rhythm, our measured biological objects is the upper human body. Accordingly, the internal volume of our experimental setup is large enough to place a human body in between. For a stable function of the gradiometer our system is designed for the suppression of an external noise in a range of ±100µT. It is enough to compensate strong geomagnetic fields which are within the limits from 40 up to 60 µT.

Table 1. Coils characteristics.

Axis	Diameter [mm]	*B* [nT /mA]	*B,max* [µT]	Number of turns
X	*1960*	*46*	*±100*	*40*
Y	*1610*	*47*	*±100*	*34*
Z	*1760*	*46*	*±100*	*36*

To verify the efficiency of our experimental setup, we have applied the simple circuit depicted in Figure 1 for magnetic noise reduction. For this purpose we have placed three pick-up fluxgate sensors perpendicularly to each other inside the working volume. These fluxgate sensors operate on frequencies from DC to 1 kHz and measure a magnetic field in a range of ±100µT with an accuracy of up to 1nT.

During our tests this system has compensated the magnetic field of the earth and has created a homogeneous magnetic field in a volume of 6.5 dm^3 with an intensity of approximately 10 nT. The attenuation of the ambient magnetic noise was measured with an independent fluxgate sensor (Teslameter FM GEO-X from “Projekt Elektronig GmbH”). The pick-up magnet sensor was placed in the centre of the ring system (about 3 cm from the compensation sensor). We obtained an attenuation of about 30-25 dB for low frequencies up to 1 Hz. Output signals from the magnetometer were obtained with and without the use of active shielding (see Figure 5). We can see that for higher frequencies the attenuation decreases, which is due to the transfer function of the whole system.

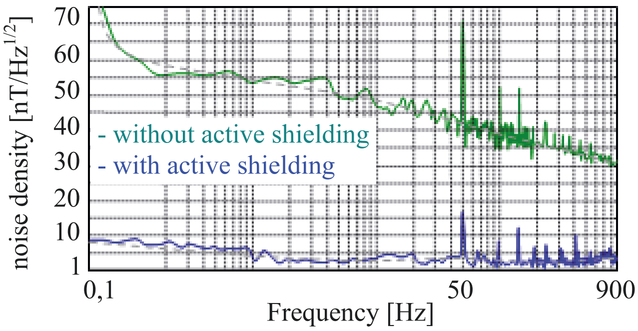

Figure 5: Noise spectrum with and without active magnetic shielding.

The remaining dominating noise results from the industrial power supply (50 Hz in Europe). The reason was the use of the current amplifier which is connected to the general power supply. We expect that such noise can be reduced up to -80 dB by the implementation of the second-order gradiometer.

The next step of our research will be the development of more sensitive fluxgate sensors which features smaller dimensions and provides constant accuracy even in non-stabilized temperature environments. Today, the fluxgate sensors have a spectral noise density of up to 2pT/$Hz^{1/2}$ [5]. In the future we plan to attach such sensors to the second-order gradiometer. This procedure should considerably increase the measurement sensitivity and, likewise, reduce the level of magnetic noise in the measured volume.

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